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Sir:

Transmitted herewith for filing is a PROVISIONAL APPLICATION of **Peter SKOVGAARD** residing at **Birkerod, DENMARK** for **AN OPTICAL COUPLER, METHOD OF ITS PRODUCTION, AND USE THEREOF**. The application comprises a 13 -page specification and 11 sheets of drawings.

Accompanying this application for filing is:

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AN OPTICAL COUPLER, METHOD OF ITS PRODUCTION AND USE THEREOF

FIELD OF INVENTION

The present invention relates to a method of producing an all-fibre Photonic Crystal Fibre coupler that can couple light from at least two light sources, such as from several transverse multi mode light sources into one single multi mode fibre.

BACKGROUND OF THE INVENTION

About 10 years ago, a new family of optical fibres has appeared, called double cladding fibres. They consist of two waveguides imbedded into each other; an inner and an outer guiding region. Typically, the inner guiding region is a single mode core, whereas the outer region typically is a multi mode core, also called inner cladding.

Microstructured optical fibres, also known as Photonic Crystal Fibres (in the following called PCFs), holey fibres, hole-assisted fibres and by other terms, is a relatively new class of fibres where the guiding mechanism is provided by introducing air holes into the fibre. These holes typically run parallel with the fibre and extend all the way along the fibre length. The guiding principle can either be based on Total Internal Reflection (TIR) such as in traditional optical fibres, or the Photonic Bandgap (PBG) principle. For TIR-based fibres the waveguide (core) typically consists of solid glass having a larger refractive index than the effective refractive index of the surrounding cladding material, which includes a number of closely spaced holes.

In resent years, PCFs have been developed to also show double cladding features. Here, a ring of closely spaced air holes (air-clad) 13 will define the multi mode inner cladding. Fibres with air-clad and their fabrication are described in US05907652 and WO03019257 that are incorporated herein by reference. The Numerical Aperture (NA) is mainly given by the distance between these holes and can take values from below 0.2 all the way up to more than 0.8, although typical values lies around 0.6. The core at the centre is typically designed for single-mode operation although multi-mode is also used. In a PCF with a microstructured inner cladding 12, typically holes 11 are placed to lower the effective refractive index. The core 10 may be formed by leaving one or more holes near the centre (see Fig. 1). Alternatively, the core 20 can simply be defined by using a solid material 21

with a higher refractive index than the rest of the inner cladding. Again an air-clad is formed by a ring of holes 22 (see Fig. 2).

A typical use for double cladding fibres is to efficiently convert low quality, low brightness light from *e.g.* semiconductor lasers to high quality, high brightness light. Brightness is defined as optical power per solid angle per area. For multi mode fibres, conservation of brightness means that the NA multiplied with the waveguide diameter is a constant before and after the coupling/conversion.

The brightness conversion is done by doping the core with a rare earth dopant and pumping this with the multi mode light. The rare earth atoms will absorb the pump light and re-emit the energy at lower photon energies. Since the emission will happen through stimulated emission, this light will be guided in the mode core. Typically single mode operation is preferred, but multi-mode operation is also relevant.

This conversion method can be very efficient (up to around 80 %) and the brightness can be improved by more than a factor of 100. Such light sources are often used as popular alternatives to high brightness solid state laser, since they are less bulky and far more efficient.

The limiting factor for the traditional fibres is the refractive index of the cladding material covering the inner cladding/pump guide. A low refractive index will result in a high NA of the pump guide. This, in turn, will allow either a smaller inner cladding diameter or the coupling of higher optical powers into the guide. Smaller inner cladding diameter means that the pump intensity is increased, which will allow higher efficiency and shorter laser cavities. The current state of the art for non-PCFs is to use a Fluorine-containing polymer cladding with a low refractive index. This will result in an NA of about 0.45. The problem with this is that such a polymer cladding often has problems tolerating the high optical powers, and will burn or degrade over time.

The PCFs, on the other hand, can achieve very high NAs and may be fabricated using only glass-based materials. This means that the inner cladding diameter can be reduced and that the thermal problems are alleviated. Also, there are further advantages, which will be outlined in the following.

When coupling light into a double-cladding PCF, there are a few considerations to make. To make full use of the high NA of the PCFs, one can use free space optics, such as lenses to couple the pump light into the inner cladding. An example can be seen in Fig. 3, where pump light from a single source, for example a fibre 30 delivering a pump light, is to be coupled into a single end of a PCF 31. The first (slow) lens 32 collimates the light 33 from the pump fibre, whereas the second (fast) lense 34 focuses the light into the inner cladding. This approach has the disadvantage that only one pump fibre can be used. Also, such a solution typically has only a coupling efficiency of 80-90 %, has high reflections, is sensitive to mechanical drift and instability and sensitive to contamination. Finally, such solution makes packaging design for a commercial device complicated and expensive.

All-fibre pump multiplexers have been developed by several companies, such as ITF, OFS and Nufern. In such couplers, several pump fibres 40 are bundled together and heated to temperatures near melting and tapered 41 (see Fig. 4). Using a slow enough taper, the light from each pump fibre will merge and the down-taper of the diameter will slowly (adiabatically) increase the NA up to 0.45 or even higher.

The problem with these traditional fibre couplers is that the high NA (higher than 0.3) at the output presents a challenge which until now have not been solved. The object of the invention is thus to provide a fiber coupler for coupling two or more light sources with which is improved with respect to the prior art fiber couplers, and in particular a fiber coupler which is improved with respect to low loss.

SUMMARY OF THE INVENTION

The inventors has thus found that to guide this high NA light, the cladding must be made with a very low refractive index material, which typically means either air or polymer. The polymer has the aforementioned problems with high optical powers. Using air gives a challenge in the mounting, as the fibre must be suspended to let air surround the fibre. The air-surrounded solution requires that the sides of the taper must be kept clean, since any contamination, such as a dust particle, will scatter light away from the waveguide.

The inventors have thus realised a solution that solves all the following demands.

- All-fibre solution, preferably fusion spliced.

- All-enclosed solution, where a reduced amount and preferably essentially none of the guided light reach the outside edge of the fibre.
- A solution with no use of polymer material in contact with pump light.
- A solution where several pump fibres can be used.
- A solution where low NA can be converted to high NA without significant loss of optical brightness.

This is done by providing a coupler as defined in the claims.

The coupler comprising in a first end region having a plurality of separate input fibres. A plurality of input fibers includes at least two input fibers. The input fibers may be identical or the may be different from each other. In principle any optical fiber can be used as input fiber. In a second region the input fibres are tapered to smaller dimension and the input fibres are fused together. The tapering section and the fused section may are both included in the second region and are defining the second region. In other word the length section including tapering of individual input fibers and fusing of the input fibers constitutes the second region. The input fibres may be fused together partly or totally in the section where they are also tapered. These fusion and tapering sections may thus be more ore less overlapping. The fused-together input fibres may be tapered to smaller dimension; at least in the tapered part of the coupler. The second region in at least a part of its length comprises an arrangement of holes surrounding the input fibers. By the term "an arrangement of holes" is meant an annular cladding with a plurality of holes which is preferably essentially parallel with each other and is extending in the length direction of the coupler. The arrangement of holes may be provided by an outer layer surrounding the more or less fused-together input fibres and comprising an arrangement of air holes surrounding the coupler at least a length section of its second region. The coupler may further comprise a third section where the input fibers are fully fused to each other. Said third section may preferably include an output end having an air-clad.

The arrangement of holes may e.g. be in the form of a plurality of holes which seen in cross section form a ring of holes. Alternatively the arrangement of holes may be a plurality of holes which seen in cross section form two or more rings of holes or an annular pattern of holes. The size of the holes may be identical or the may vary, periodically or non-periodically. In one embodiment the arrangement of holes is in the form of a plurality of

holes which seen in cross section form a ring of holes where the space between the holes are less than the diameter of the smallest hole, preferably the hole has identical diameters.

As the input fibres in the second region are tapered down in dimensions, they will leak some of their light away. By providing the arrangement of air holes surrounding the more or less fused-together tapered input fibre in the second region, it has been found, thanks to the invention, at least a part of this leaking light may be collected and guiding to an output end of the coupler. The output end may then be coupled, for example by fusion splicing or but-coupling, to an air-clad fibre. It is preferred that the output end of the coupler and an air-clad fibre that is coupled to have substantially similar NA and dimensions of the air-clad. This is preferred in order to provide lowest possible coupling losses (highest possible coupling efficiency).

A variety of numbers of input fibres are feasible, for example, 2, 3, 6, 7 or more. The input fibres are typically multi-mode pump guiding fibres with a pure silica core and an F-doped cladding. However, one or more of the input fibres may also be a single mode fibre. The input fibres may have a core dimensions ranging from at least 2 um to 1000 um. Typically, single mode input fibres have core diameters ranging from 2 um to 30 um, whereas multi-mode fibres have cores ranging from 50 um to 1000 um. However, the present invention is not restricted by these dimensions of the input fibres. The multi-mode input fibres are typically characterised by an NA in the range from 0.15 to 0.25, but other values are feasible as well.

The invention also includes methods for producing such couplers, which includes methods for controlling the size of the air holes along the taper.

BRIEF DESCRIPTION OF THE DRAWINGS

In the following, by way of examples only, the invention is further disclosed with detailed description of preferred embodiments. Reference is made to the drawings in which

FIG. 1 shows schematically the end face of a double cladding (also known as air-clad) Photonic Crystal Fibre after cleaving. The ring of closely spaced, larger holes surrounding

the multi mode guide can be seen. The smaller holes within the inner cladding defining the core can also be seen.

FIG. 2 shows schematically the end face of a double cladding Photonic Crystal Fibre after cleaving. The ring of closely spaced, larger holes surrounding the multi mode guide can be seen. Here, the single mode core is defined through control of the refractive index.

FIG. 3 shows schematically a typical method for coupling lower NA light from a pump fibre into the higher NA PCF.

FIG. 4 shows schematically a tapered, fused pump multiplexer as it is realised with non-PCF technology.

FIG. 5 shows schematically how the individual input fibres may be positioned when inserted into a ring element, during the production of a coupler according to the invention.

FIG. 6 shows schematically a preferred embodiment of the present invention. Individual input fibres 61 have been inserted into a ring element and the assembly of ring element and input fibres has been tapered down in size (section B which is the second region). At the output end (section C which is the third section), the coupler is an air-clad, MM fibre.

FIG. 7 shows schematically how a number of pump fibres are inserted in a ring element.

FIG. 8 shows schematically how hermetically sealing of one end of the ring element allows individual pressure control of the inner holes.

FIG. 9 shows schematically an example of how heating near the input end will collapse all cavities and holes and thus hermetically seal this end.

FIG. 10 shows schematically another example of how heating near the input end will collapse all cavities and holes and thus hermetically seal this end.

FIG. 11 outlines schematically a preferred embodiment of a method and a coupler according to the present invention. Vacuum is provided with a rubber hose at the right hand side. Combination of heating and pressure control at region 2 (second region) will collapse

the interstitial holes and fuse together the input fibres. The input fibres are separate (loose) in the input end. Note that the interstitial holes may collapse without significant diameter change of the individual MM cores, if tapering is not performed during the heating. The additional initiation of mechanical pulling (at region 3(third region)) will taper the diameter down to the desired dimension. The three inset show the cross-section of the coupler at the sections 1, 2 and 3. The coupler is cleaved in region 3 to provide the final output end of the coupler. Inset 3 shows the end facet of the output end of the coupler (dashed lines indicate fused together interfaced between input fibres, as well as between input fibres and inner part of the ring element. The holes in the ring element are kept open due to internal pressure in the sealed off holes.

DETAILED DESCRIPTION OF THE INVENTION

As stated before, there is a need for devices and methods of coupling the output from several semiconductor diode pumps into one high NA, double cladding fibre. It is an object of the invention to provide an all-fibre, all-silica, high NA coupler solution without exposed waveguides.

In the following a method of fabrication according to a preferred embodiment of the present invention will be outlined. For illustrative purposes there is chosen a specific example of a coupler with 7 input fibres. The input fibres are all-glass solid MM fibres with an NA of 0.22 and core/cladding diameters of 105 μm and 125 μm, respectively.

The ring element is basically two thin tubes of glass with a large number of holes situated in between (see afore-mentioned reference WO03078338). Typically there are more than 100 holes in such a structure. The ratio between the inner and outer diameter is typically about 0.8. The inner diameter is in this example chosen to allow 7 input fibres to be slid into the tube (see Fig. 5 and 7). This means that the inner diameter must be chosen larger than 375 μm in the case of the outer diameter of the input fibres being 125 μm.

Cleaving and sealing the ring element: Since the ring element is made of all-glass it is easy to cleave the ring element at a well-controlled length. The cleaving may for example be done by scratching the ring element with a diamond tool and applying a mechanical force to cleave the ring element at the scratched position. A typical length range will be 6-12 cm. A well-controlled, short duration heating of the end of the cleaved ring element will melt the

end and thus hermetically seal the holes. It is preferred that the inner diameter of the ring element is substantially maintained.

Stripping and inserting the input fibres: As an example, 7 lengths of standard MM fibres are stripped at a length 3 cm longer than the ring element. The input fibres 70 are slid into the ring element 71 as shown in Fig. 7, such that part of their length is within the center opening of the ring element, and part of their length is outside 70. Hence, the input fibres have individual, separate ends that may be coupled to from individual light sources.

It is preferred to apply pressure control (for example vacuum) during fabrication. A silicone tube may be attached to one end of the ring element (typically the opposite end of the end wherein input fibres have been inserted). The silicone tube can be connected to a vacuum pump that will force interstitial holes (marked as black regions in Fig. 5) to collapse when heating the ring element that comprising input fibres.

It is preferred to sealing the input end during fabrication. This is done to fixate the position of the input fibres within the ring element as shown schematically in Fig. 9. This allows pressure control inside the ring element. The sealing can be done at the end of the ring element 90 (Fig. 9), or some distance 100 from the end (Fig. 10). In either case, the heating should be strong enough to allow surface tension to collapse all holes. Note that there may be no tapering in this step. This means that the core diameter of each individual MM fibre may remain unaltered. The core might no longer circular, but due to gradual deformation, optical loss out of the core can be kept at a minimum. Note, that even if this should happen, there are still the holes in the ring element to guide this light.

Mounting in taper machine: In a preferred embodiment, a commercial splicer like the Vytran LDS-1250 is use for heating and tapering. This machine is specially designed to be able to produce well-controlled tapers. Of course, also other heating/pulling arrangements could be made. The ends of the ring element are attached at the fixtures. Note that since the input fibres are melted into the ring element, this mounts securely all elements.

Heating and tapering: Simultaneous heating and pulling will allow well-controlled tapering, both in terms of reduction ratio, final diameter and taper shape. The setup is sketched in Fig. 11.

Cleaving: the taper is preferably cleaved somewhere within region 3 in Fig. 11. For input fibres comprising a high-index core and a low-index cladding (for example a pure silica core and an F-doped cladding), the up-doped core material is still embedded within the ring of holes. This might result in an inhomogeneous distribution of the guided light at the output of the coupler. However, as long as the light is guided within the NA of the ring element, this is not a problem as the light may be coupled to a high NA, air-clad fibre with matching NA and air-clad dimensions. By matching air-clad dimensions is meant that the dimension of the inner cladding (or pump core) of an air-clad fibre with an active core is matched to the inner dimension of the air-clad in the output end of the coupler. This dimension is marked ID in Fig. 11.

Note that mode mixing in an air-clad fibre that pump light is coupled to via the coupler will typically homogenise the pump light distribution.

Splicing to an air-clad, active fibre: Since the output end of the coupler and the air-clad fibre are preferably designed to fit each other, splicing these two together with high quality optical performance is feasible using standard splicing equipment, such as Vytran FFS 2000, using suitable adjustments of splicing parameters, including temperature, heat, exposure time etc.

To make coupling efficient, one must try to conserve the brightness of the light. That is the same as saying that the NA multiplied with the waveguide diameter must be constant throughout the entire taper and that the transmission loss must be low. As an example, if the NA is increased from 0.22 to 0.6, the diameter can be reduced to about one third of the size. Note that this means that the intensity increases by a factor of 9.

It has been found that it is possible to taper a multi-mode (MM) fibre with relatively low loss – this is demonstrated in Danish Patent Application PA 2004 00447 that is incorporated herein by reference. As an example, a passive air-clad fibre (a fibre comprising a large MM silica core and an air-clad) was tapered down while efficiently conserving brightness. Reducing the diameter by a factor of 2 and increasing the NA accordingly through the reduction in wall thickness between holes in the air-clad, transmission was better than 98 % and brightness was reduced by less than 2 %.

Assume that the NA of the input MM fibre is 0.22. It is desired to make a MM fibre with an NA of 0.6, the core diameter can be reduced by 0.6/0.22 = 2.7. As stated before such a high NA cannot be supported using polymer cladding (and also polymer cladding is undesirable due to high power reliability). Such a high NA is possible using an air-clad.

In the following further description of the tapering shall be given.

The present inventors have realised that tapering can be made for ring elements such as those described in WO03078338. Also such ring elements comprising a plurality of input fibres inserted into their center hole may be tapered down. The tapering may be performed using commercially available tapering equipment as for example from Vytran. Ring elements and their fabrication are disclosed in WO03078338 that is incorporated herein by reference. See e.g. Fig. 17b in WO03078338, where a schematic illustration of a ring element that may be used for the present invention is shown. Typically, the ring element, before tapering, has inner dimension (dimension of opening) in the range from around 200 μm to around 3000 μm. The holes in the ring element may maintain their relative sizes during tapering, this means that the entire structure reduces in size. Also the wall thickness, that is, the size of the glass material in-between the holes around the MM core reduces in size (the MM core meaning the fused-together input fibres and part of the ring element inside the ring of holes (for example the region of dimension ID, as indicated in Fig. 11)). It is a further advantage that since the NA is almost linearly dependent on this thickness (as described in WO03019257), a down taper will automatically mean an increase of the NA. This means that the ring element can be made with fairly large wall thicknesses and thus fairly robust. As the ring element is tapered down, the fairly large wall thickness is reduced and the NA is increased. Hence, in an output end (where the ring element has the smallest dimension of the taper) the NA is highest.

The present inventors have further found that down-tapering be done on ring elements comprising solid material with low transmission loss. For example, a down-tapering of a MM, air-clad fibre can be done while efficiently conserving brightness. Reducing the diameter by a factor of 2 (and increasing the NA accordingly), transmission has been found to be better than 98 % and brightness maintained to within 2 %.

Some preferred embodiments have been shown in the foregoing, but it should be stressed that the invention is not limited to these, but may be embodied in other ways within the subject-matter defined in the following claims.

CLAIMS

1. An optical coupler for coupling light form a plurality of input fibres into one fiber, said optical coupler comprising

- a first region with at least two input fibers;
- a second region wherein said input fibres are tapered and are fused together;

wherein said input fibers in at least a part of the length of said second region of the coupler are surrounded by an arrangement of holes.

2. An optical coupler according to claim 1, wherein said coupler further comprises a third section where the input fibers are completely fused to each other, said third section comprises a single output end, said output end preferably comprising an air-clad in said single output end.

3. An optical coupler according to any one of the claims 1 and 2, wherein said input fibres are solid fibres.

4. An optical coupler according to any one of the claims 1-3, wherein a majority of said input fibres are multi-mode fibres.

5. An optical coupler according to claim 4, wherein all of said input fibres are multi-mode fibres.

6. An optical coupler according to claim 4, wherein one of said input fibres is a single-mode fibre.

7. An optical coupler according to any of the claims 2 to 6, wherein said output end has an NA larger than 0.45, such as larger than 0.50, such as larger than 0.55, such as larger than 0.60.

8. An optical system comprising an optical coupler according to any of the claims 1 to 6 and an air-clad optical fibre, said air-clad optical fibre having substantially similar NA and air-clad dimension as the optical coupler.

9. A method for fabricating an optical coupler, said method including the steps of

- providing a plurality of input fibres

- proving a hollow ring element comprising a ring of holes, preferably substantially parallel to the center axis of the ring element, said ring element has a central opening
- optionally sealing off holes in said ring element in at least one section of said ring element
- inserting said plurality of input fibres into said central opening such that a part of their length is within said opening and another part of their length is outside said opening
- heating said ring element at a position or in a section where said input fibres are present in said opening
- tapering said ring element in a section where said input fibres are present in said opening
- optionally performing said heating and tapering in the same step
- optionally apply a less-than-atmospheric pressure in said opening during said heating and/or tapering
- optionally cleave said ring element, preferably at a section of smallest dimension after tapering

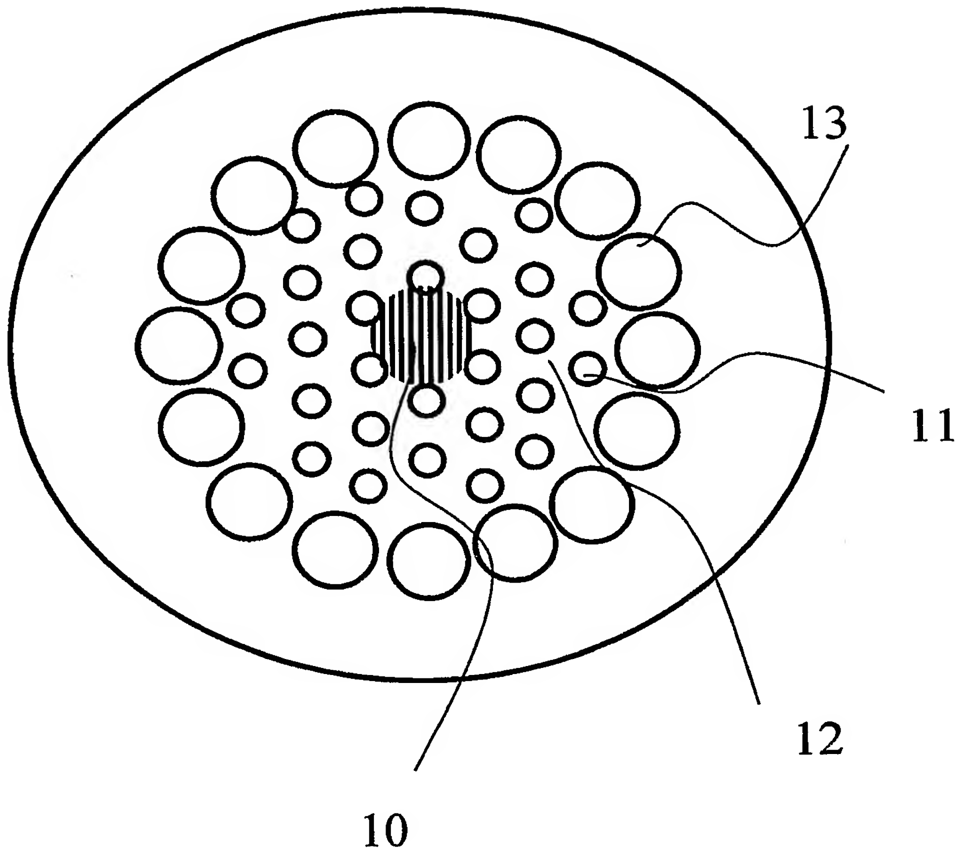

Fig. 1

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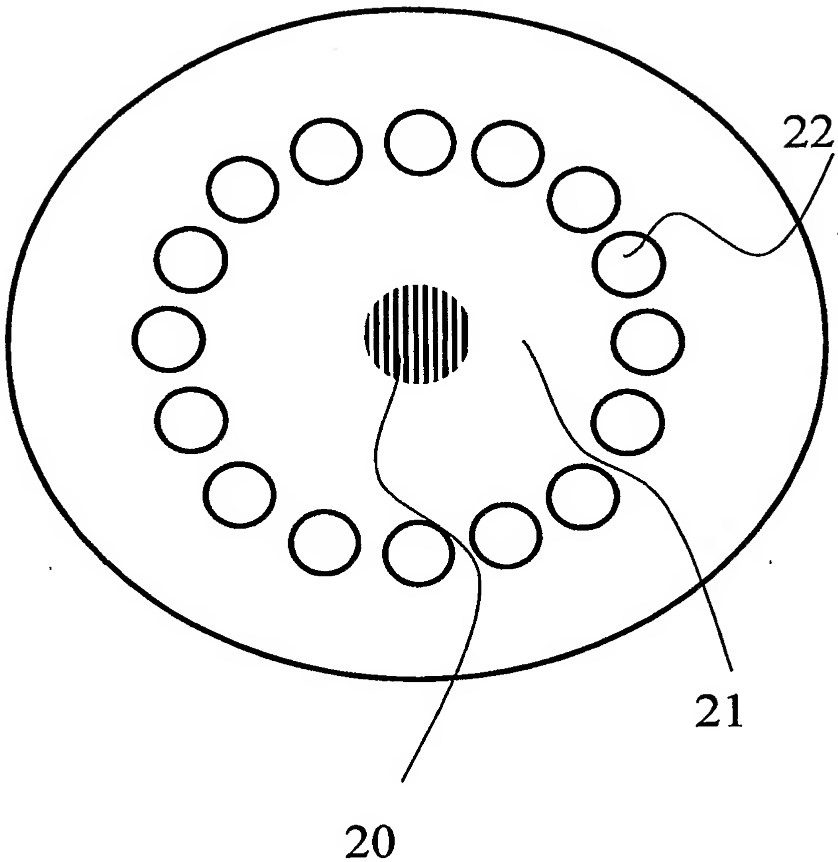

Fig. 2

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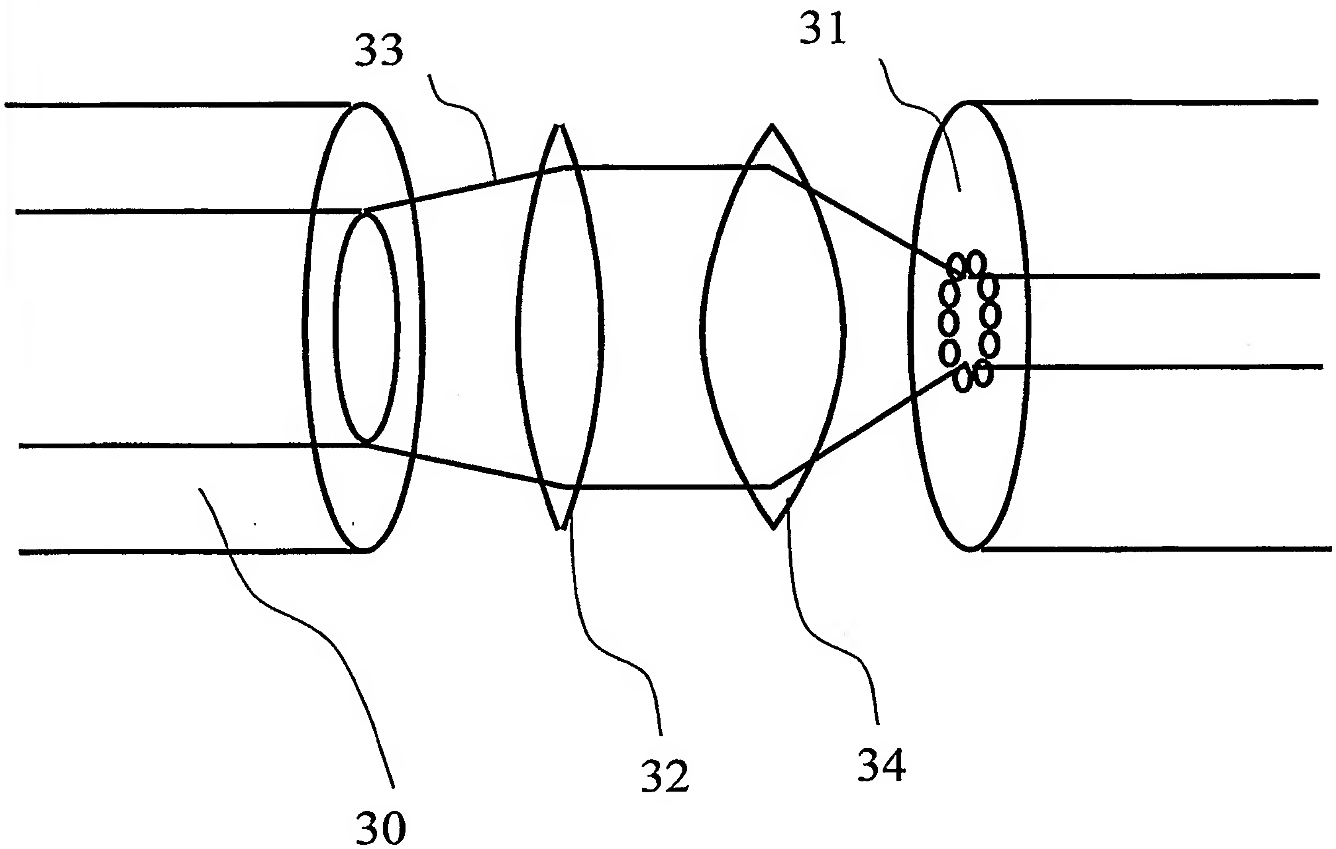

Fig. 3

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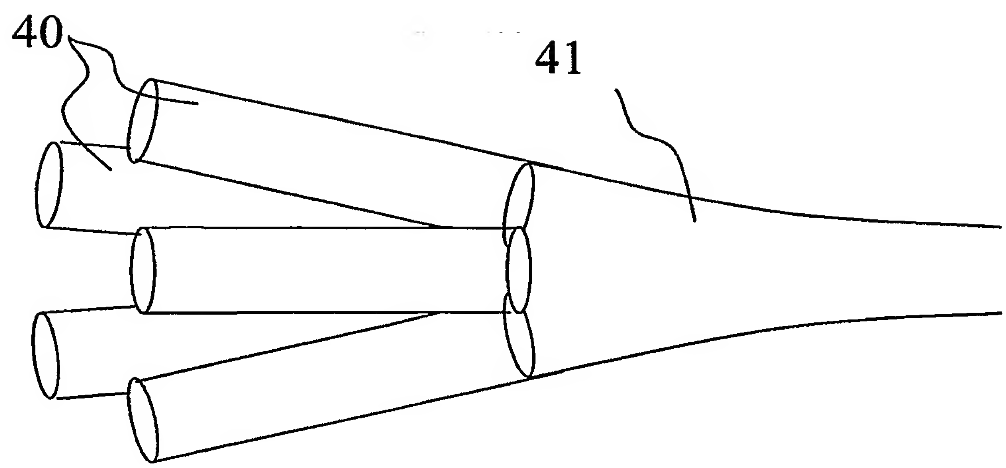

Fig. 4

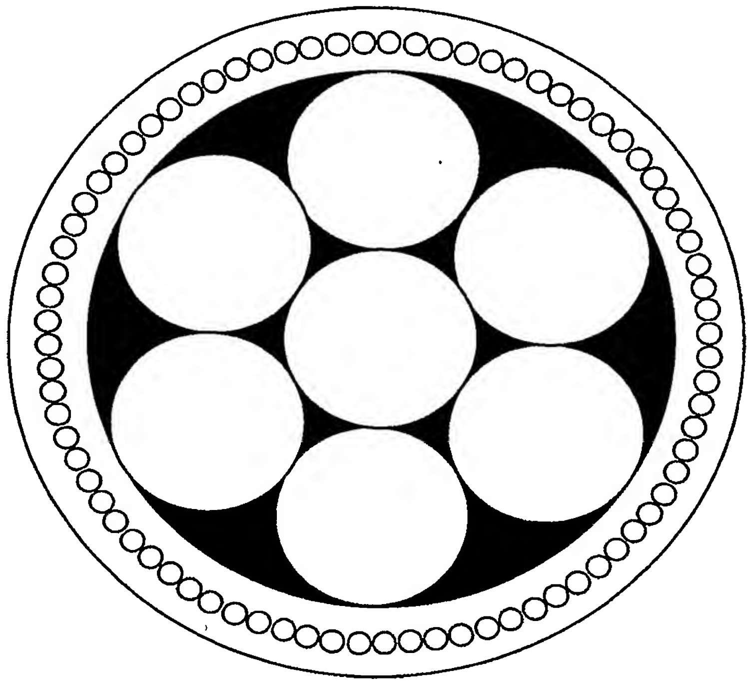

Fig. 5

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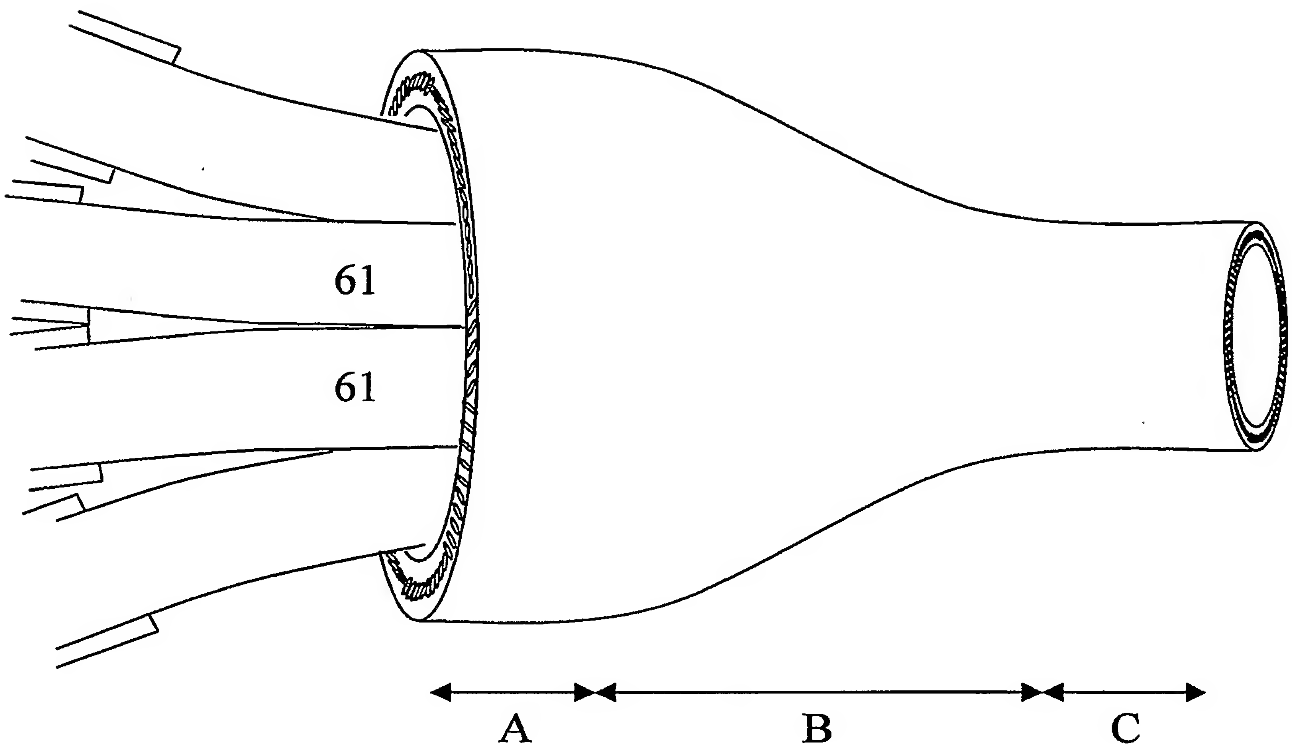

Fig. 6

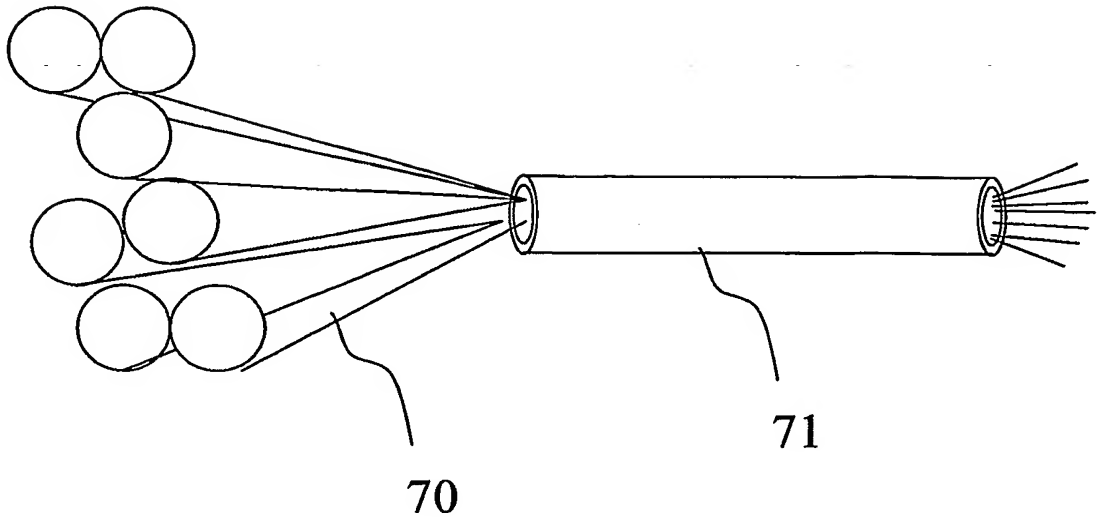

Fig. 7

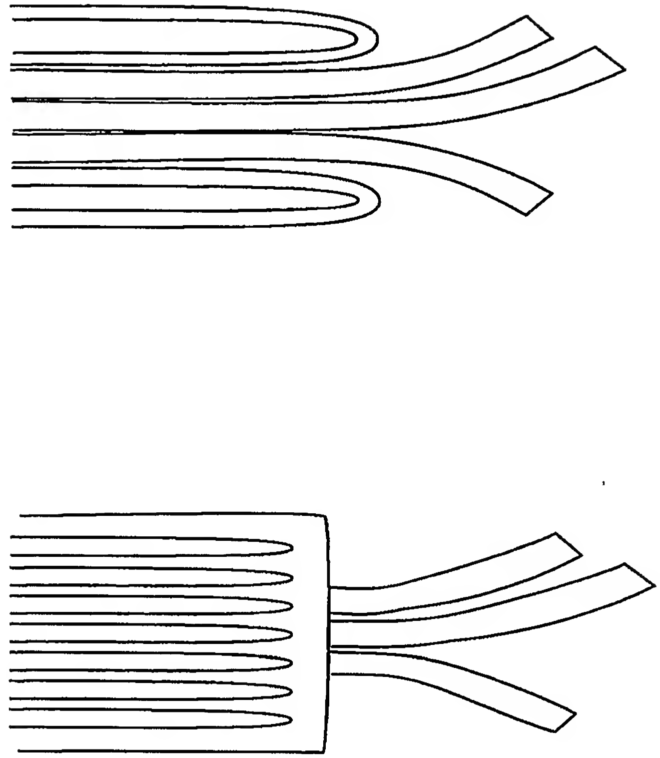

Fig. 8

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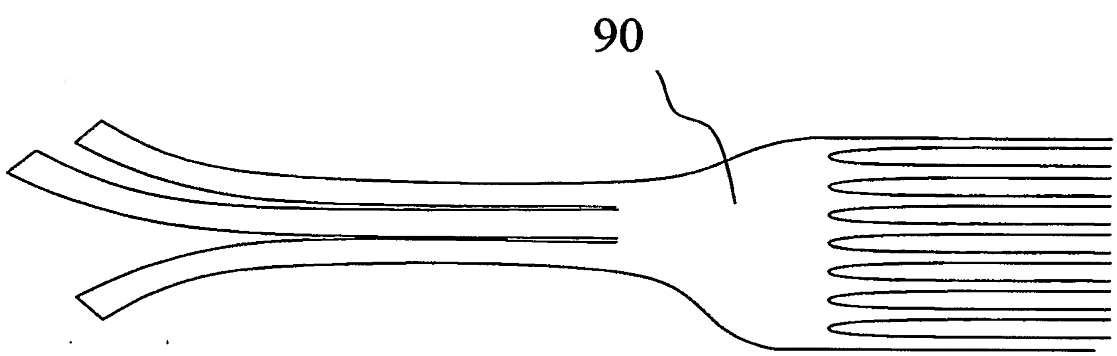

Fig. 9

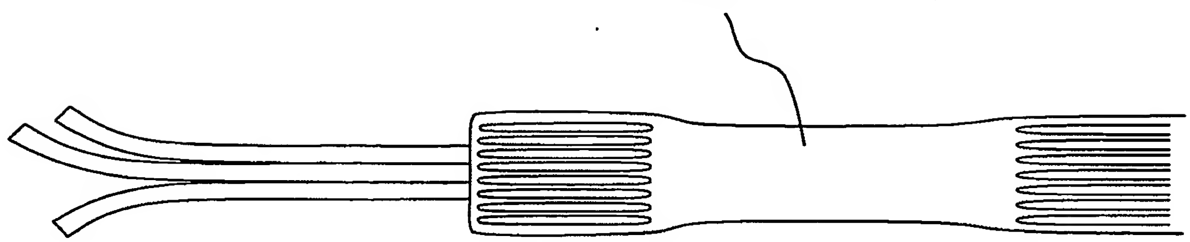

Fig. 10

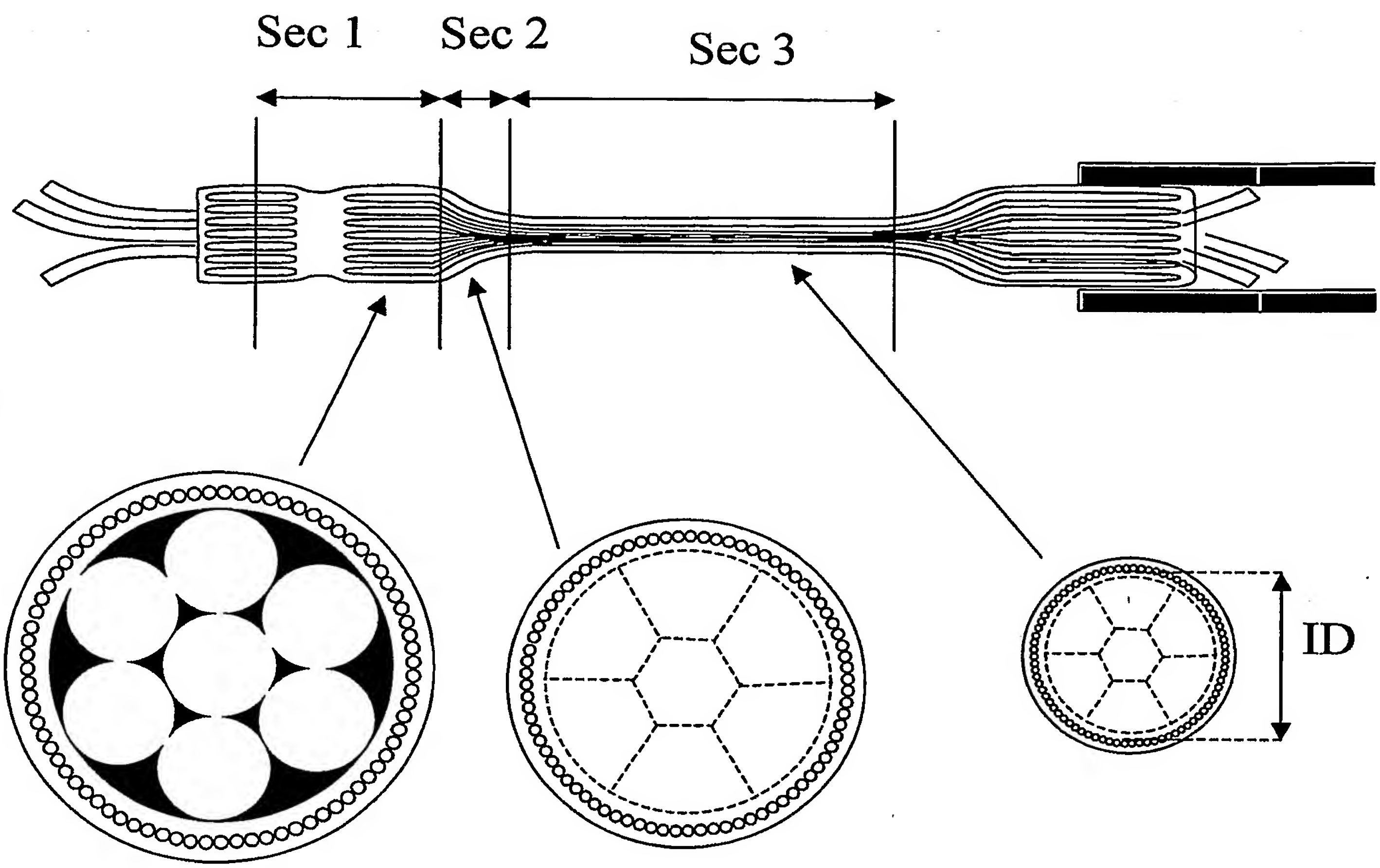

Fig. 11